Considering body mass differences, who are the world's strongest women?

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ABSTRACT

VANDERBURGH, P. M. and C. DOOMAN. Considering body mass differences, who are the world's strongest women? *Med. Sci. Sports Exerc.*, Vol. 32, No. 1, pp. 197–201, 2000. **Purpose:** Allometric modeling (AM) has been used to determine the world's strongest body mass-adjusted man. Recently, however, AM was shown to demonstrate body mass bias in elite Olympic weightlifting performance. A second order polynomial (2OP) provided a better fit than AM with no body mass bias for men and women. The purpose of this study was to apply both AM and 2OP models to women's world powerlifting records (more a function of pure strength and less power than Olympic lifts) to determine the optimal model approach as well as the strongest body mass-adjusted woman in each event. **Methods:** Subjects were the 36 (9 per event) current women world record holders (as of Nov., 1997) for bench press (BP), deadlift (DL), squat (SQ), and total (TOT) lift (BP + DL + SQ) according to the International Powerlifting Federation (IPF). **Results:** The 2OP model demonstrated the superior fit and no body mass bias as indicated by the coefficient of variation and residuals scatterplot inspection, respectively, for DL, SQ, and TOT. The AM for these three lifts, however, showed favorable bias toward the middle weight classes. The 2OP and AM yielded an essentially identical fit for BP. **Conclusions:** Although body mass-adjusted world records were dependent on the model used, Carrie Boudreau (U.S., 56-kg weight class), who received top scores in TOT and DL with both models, is arguably the world's strongest woman overall. Furthermore, although the 2OP model provides a better fit than AM for this elite population, a case can still be made for AM use, particularly in light of theoretical superiority. **Key Words:** WEIGHTLIFTING, ALLOMETRIC SCALING, POLYNOMIAL MODELS

Allometric modeling (AM), one technique for modeling the relationship of body size to some physiologic marker, has received recent interest in the exercise sciences (1–6,8–20). Such modeling has several attractive features. First, it is based on the relationship $y = ax^b$, where a and b are constants, y is the outcome variable (e.g., strength) and x is the body size variable (e.g., body mass). This has theoretical appeal because one should have zero level of y with zero body size and because the exponent b allows for the curvilinear relationship expected (3,9). Second, a simple body size-adjusted index of performance, $y \cdot x^{-b}$, can be created to allow for individual or group comparisons with the independent influence of body size partitioned out (4,14,19,20). Third, in studies involving strength or maximal oxygen uptake adjusted by body size, AM accommodates well the theoretical body size exponent of 0.67, or 2/3. The 2/3 exponent has been widely supported because strength or maximal oxygen uptake, both two-dimensional constructs (related to cross-sectional area), should be related to body mass (a three-dimensional construct) raised to the 2/3 power (3).

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Such modeling has been applied to many exercise science settings. Nevill et al. (8) have used AM to demonstrate empirically what theory has predicted regarding the relationships between body mass and such variables as $\dot{V}O_{2max}$ or distance run time (9) and height and $\dot{V}O_{2max}$. Batterham et al. (5) have used AM to model left ventricular mass relative to body mass. Allometric models have been applied to indices of fitness including grip strength (17), two-mile run time (16), indoor rowing (15), and maximal effort cycle ergometry (13). AM has been used to elucidate the contributions of growth and/or maturation on changes in $\dot{V}O_{2max}$ in children (1,2,10,11). Croucher (7) used AM to determine, "kilogram for kilogram," the strongest man of the then current world record Olympic weightlifters. The reported exponent of 0.58 allowed for comparison of all the world record holders' weight-adjusted index (max weight lifted divided by body mass raised to the 0.58 power). The lifter with the highest index was labeled the "world's strongest man." Such a convention is appealing because it provides for comparison of strength between subjects of vastly different body size. In effect, AM provides a convenient method of eliminating weight classes.

The potential misuses of AM have also received considerable attention. Batterham et al. (6) criticized certain applications (8) of multivariate AM (more than one independent variable, e.g., body mass and height) and advised caution in the interpretation of resulting individual exponents. Vanderburgh et al. (18) offered tutorials on the handling of group differences with AM-derived indices as well as a real data example of how traditional linear modeling can yield a less than appropriate data fit for simple strength to body size relationships (12).

Most recently, however, AM itself was challenged as perhaps not being an appropriate model for the body mass to strength relationship in elite Olympic-style men and women weightlifters. Batterham and George (4) reported that a second order polynomial (2OP) was found to provide a more suitable fit for the curve defined by body mass and the world record total lift for the "snatch" and the "clean and jerk." They reported a clearly observable pattern of body mass bias with AM that favored middle weight class lifters. In the analysis of the women's data they acknowledged that model fit was not as precise as that of the men's perhaps because: "Elite women weightlifters may be expected to display relative heterogeneity across the group for factors that may cloud the body size-muscular function relationship including technique, training status, psychological preparation, nutrition, and ergogenic aid use." Nevertheless, model precision, even for the women, still yielded a reported correlation of 0.96 (actual vs predicted), with a normal distribution of residuals and no body mass bias.

To date and to our knowledge, such modeling (AM or 2OP) has yet to be applied to world record lifts for powerlifting events (bench press, squat, and deadlift) for either men or women. The term "powerlifting" is actually less about power and more about pure strength than are the Olympic lifts, which incorporate a significant power component for high achievement. This difference may be physiologically important because strength is perhaps more a function of muscle cross-sectional area, the very factor closely linked to the underlying theory of AM fit. One could argue, then, that the world's strongest woman, for example, is more likely a powerlifter and not an Olympic-style weightlifter. The purpose of this investigation, then, was to apply AM and 2OP modeling to women's world record powerlifting events to compare model fit and to use these models to determine the world's strongest body mass-adjusted women.

SUBJECTS

Subjects were the current nine world record holders for each of the four International Powerlifting Federation's (IPF) events: bench press (BP), squat (SQ), deadlift (DL), and total (TOT) lift (BP + DL + SQ) according to the IPF as of November, 1997 (IPF official internet address: www.ipf.com). Therefore, similar to the manner in which other world record data are analyzed and reported for athletes in other sports, informed consent was not obtainable, nor was it warranted in this investigation. The data from the heaviest weight class, 90^{+}kg body mass, were not included in the present analysis because it is the only weight class with no ceiling on maximum allowable weight. This would likely have had a spurious effect on any modeling (4).

PROCEDURES AND ANALYSES

Body mass was assumed to be the actual weight class in accordance with the procedures of Croucher (7). This was primarily because these values were not available for world records, some of which date as far back as 1984. This approach, however, appeared to be prudent for two reasons. First, since such world class weightlifters are widely known to "cut weight" to achieve the maximal allowable weight, they can be assumed to be at or very near the actual weight class cut-off. Second, our own analysis of the top three women finishers in the Women's World Powerlifting Championships of 1997, whose body mass values are provided (from the aforementioned official IPF internet address), substantiated the estimated error from this approach as being insignificant. We calculated the average deviation below the maximal allowable weight to be 0.7 kg (SD = 0.2 kg). Assuming, then, a 1.0-kg error (arguably worst case) in body mass lead to mean errors of 1.2% for the AM and 1.5% for the 2OP models in the prediction of TOT (as reported in the results section of this investigation). These errors, again worst case, are arguably insignificant and would have had little to no practical effect on the present investigation.

To determine the optimal exponent for the $y \cdot x^{-b}$ index for each lift, AM was employed. Its details are discussed elsewhere (8,9,18). Briefly, AM assumes that the best-fit curve of the body mass (M) to strength (S) relationship is of the form $S = aM^b$ then uses log-linear regression (taking log of both sides yields $\log S = b\log M + \log a$ which is now the equation of a straight line) to solve for the value of b. Since b is actually the coefficient of the logM term, then the regression output also includes the SEE of b such that the use of any b within the 95% confidence interval results in a dimensionless index (i.e., the resulting index has no correlation with M). The second model approach 2OP was then applied to the same data in accordance with previously reported recommendations (4). Briefly, an M^2 term was added to the M term as independent variables in the regression model (i.e., $S = aM^2 + bM + c$) for each of the lifts. For the BP, the M^2 term was nonsignificant ($P > 0.5$) so the model was redeveloped using only the M term.

The nine data points (M and weight lifted) for each lift were fitted to both the AM and the 2OP with the respective best-fit curves superimposed over the data points to provide a convenient graphic depiction of potential residual patterns. Regression diagnostics recommended by Batterham and George (4) were used to closely examine model fit. Furthermore, the coefficient of variation (CV, the SEE divided by the mean of the weight lifted) for each lift was computed to more precisely quantify the goodness of fit. The CV can be more informative than the SEE alone because it is dimensionless and can be used to compare model fits across different events.

Comparison of women's models with those of men's in powerlifting events is not included in this investigation because the sport of weightlifting for women is still relatively young and probably has yet to see women's performance at the physiologic limits, particularly in the lowest and highest weight classes (because of the relatively smaller

TABLE 1. Allometric Model (AM) relationships for bench press (BP), deadlift (DL), squat (SQ), and total lift (TOT) to body mass (M).

Event	Equation	SEE of Exponent	SEE (kg)	CV
BP	$BP = 3.31M^{0.867}$	0.053	4.37	0.036
DL	$DL = 16.32M^{0.629}$	0.075	11.49	0.052
SQ	$SQ = 10.65M^{0.718}$	0.054	8.41	0.040
TOT	$TOT = 23.76M^{0.750}$	0.052	18.10	0.039

numbers of competitors in these events). This may have contributed to the less precise model fit (either AM or 2OP) of the women's records as compared with the men's in Batterham's data. Men's world records, however, are the result of both years of competition and high numbers of competitors, especially relative to women. One can arguably place greater confidence in the exponents or models developed using these data because they are likely nearer to the physiologic limit of male performance. Because one data point can significantly influence the overall AM or 2OP fit when $N = 9$, we opted to exercise caution by not comparing models by gender.

RESULTS

AM and 2OP applied to the four lifts yielded the relationships as shown in Tables 1 and 2, respectively. CV values favored the 2OP models for DL, SQ, and TOT and were essentially identical for the BP. Figure 1 graphically displays the model fit for both AM and 2OP applied to the four events.

While both models demonstrated excellent fit by most standards, the regression diagnostics similar to those recommended by Batterham and George (4) were employed to further examine model fit for bias. Specifically, scatterplots of the body mass to world records (Fig. 1) which included the best-fit curves described by the AM and 2OP models, were examined for normal distribution and possible bias of the residuals. Residual distribution can be easily evaluated by applying the Kolmolgorov-Smirnov test for normality to the residual values (actual world record minus the world record predicted by the model). Bias by body mass is best evaluated by examining the data points' position relative to the best-fit curve. If point are scattered about the curve with no apparent trend, then bias can be considered negligible. If, however, lighter and heavier subjects were below the line and middle weight subjects were above, then one could conclude that the model fit exhibited favorable bias toward middle weight subjects.

As shown in Figure 1 for the DL, SQ, and TOT, the AM model indeed displayed a notable trend to penalize those subjects in the lighter and heavier weight categories. This is clear in that the actual lifts of these individuals are below the AM curve while those in the middle weight classes are above the curve. The Kolmolgorov-Smirnov test for normality revealed

TABLE 2. Second order polynomial model (2OP) relationships for bench press (BP), deadlift (DL), squat (SQ), and total lift (TOT) to body mass (M).

Event	Equation	SEE (kg)	CV
BP	$BP = 1.63M + 16.80$	4.42	0.037
DL	$DL = -0.052M^2 + 9.00\,M - 128.87$	6.34	0.029
SQ	$SQ = -0.037M^2 + 7.147M - 89.56$	5.37	0.026
TOT	$TOT = -0.060M^2 + 15.30M - 144.54$	14.47	0.027

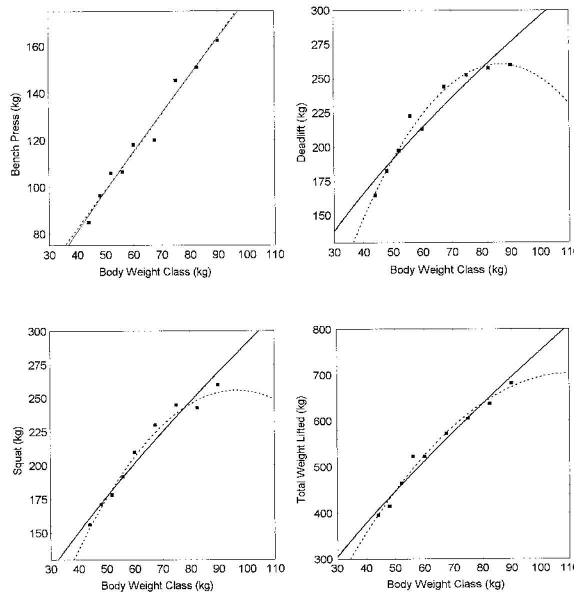

Figure 1—Bench (BP), Squat (SQ), Deadlift (DL), and Total Lift (TOT) vs Body Weight Class (BW). Squares each represent the world record lift by weight class. Dotted lines represent the 2nd order polynomial best-fit curves. Solid lines represent the allometric model best-fit. As the 2nd order polynomial demonstrated an inferior model fit for BP, the M^2 term was eliminated.

that residuals for all AM models were essentially normally distributed ($P > 0.10$). The BP model, however, displayed nearly an identical fit for either model in that the two curves are nearly coincident and the data points are scattered about the curves with no notable trend for bias. All four 2OP models indicated unbiased residuals (data points display no trend with respect to body mass) with normally distributed residuals (Kolmolgorov-Smirnov test, $P > 0.10$).

Applying both models to world powerlifting records, despite the apparently inferior model fit of AM, one can determine who the strongest woman in the world in each lift is, considering differences in body mass. This is done rather conveniently for the AM model by comparing individuals in the $S{\cdot}M^{-b}$ index, with larger index meaning higher achievement. For the 2OP models, one must compute each individual's residual score (actual minus predicted world record); higher score indicates higher achievement. As shown in Table 3, the ordinal rank of achievement does vary with the model used. In the SQ, for example, Ruth Shafer (U.S., 75-kg weight class) is considered the strongest (body mass-adjusted) lifter using the AM model but is third behind the Anne Stiklestad (Norway, 75-kg weight class) and Cathy Millen (U.S., 90-kg weight class) when the 2OP model is used.

DISCUSSION

Results of this study suggest that body mass exponents for elite powerlifting vary by event for women from 0.63 for the DL to 0.87 for the BP. The 95% confidence interval (calculated by multiplying the SEE by 1.96) contains the widely reported exponent of 0.67 for the DL, SQ, and TOT but not for BP. The exponent 0.67 is most theoretically sound (8,9)

TABLE 3. The strongest body mass-adjusted women in the world based on AM or 2OP models applied to world records for powerlifting events: bench press (BP), deadlift (DL), squat (SQ), and total lift (TOT, or the total of the three individual lifts). Home country is in parentheses followed by weight class (WC) and weight lifted (WL).

Event	AM 1st Place	AM 2nd Place	2OP 1st Place	2OP 2nd Place
BP	Li-Min Lin (Taiwan) 52 kg WC 106.0 kg WL	Marina Zhguleva (Russia) 75 kg WC 145.5 kg WL	Marina Zhguleva (Russia) 75 kg WC 145.5 kg WL	Li-Min Lin (Taiwan) 52 kg WC 106.0 kg WL
DL	Carrie Boudreau (USA) 56 kg WC 222.5 kg WL	Ruth Shafer (USA) 67.5 kg WC 244.0 kg WL	Carrie Boudreau (USA) 56 kg WC 222.5 kg WL	Ruth Shafer (USA) 67.5 kg WC 244.0 kg WL
SQ	Ruth Shafer (USA) 67.5 kg WC 230.0 kg WL	Beate Amdahl (Norway) 60 kg WC 210.0 kg WL	Anne Stiklestad (Norway) 75 kg WC 245.0 kg WL	Cathy Millen (USA) 90 kg WC 260.0 kg WL
TOT	Carrie Boudreau (USA) 56 kg WC 522.5 kg WL	Lisa Sj-strand (Sweden) 67.5 kg WC 572.5 WL	Carrie Boudreau (USA) 56 kg WC 522.5 kg WL	Cathy Millen (USA) 90 kg WC 682.5 kg WL

because muscle strength should be directly proportional to muscle cross-sectional area which, in turn, is proportional to $M^{0.67}$. Further explanation of this puzzling finding for BP requires further investigation involving perhaps detailed biomechanical analysis of the BP as well as body composition and/or anthropometric analysis of elite women bench press competitors.

Comparison of these exponents with those obtained by Batterham and George (4) for the Olympic lifts is cautionary for two reasons. First, they used the actual weights of the competitors in the highest weight category (superheavyweight, no upper weight limit). Our data include only those subjects who had a restriction for upper limit of body mass, i.e., all but the superheavyweight lifter. With no upper weight limit the confounding influence of fat mass on the body mass to weight lifted relationship cannot be controlled for. Since the superheavyweight lifter is at the extreme, her data point would likely have had a particularly significant influence on the regression curve by deflating the exponent. For the men's data (4), this was ascertained by removing this subject's data and recalculating the exponent. This was not done, however, for women so comparison with our data is not prudent.

Second, Batterham's data involves only Olympic lifts, arguably more a function of strength plus power. The present data are for powerlifting events which are more a function of pure strength and less about power and, perhaps, technique. In short, powerlifting events are functionally different from Olympic lifts and comparison of body mass exponents between them should not be done without extensive and careful interpretation. Nevertheless, a cursory examination reveals that the women's powerlifting exponents are significantly larger (considering 95% confidence intervals) than the one exponent of 0.45 reported by Batterham and George for Olympic lifts (4). This is probably because of their aforementioned inclusion of the superheavyweight subjects (which tends to deflate the exponent). Other explanations should be elucidated with further study.

Similar to Batterham and George's results (4), however, is the finding that for three of the four women's powerlifting events, the 2OP model provides a better fit and satisfies the regression diagnostics more satisfactorily than the AM. The BP AM and 2OP models yielded nearly an identical fit although the 2OP was not a second- but a first-order polynomial. In fact, as Figure 1 shows, the fit is nearly linear with an origin near zero, suggesting that ratio scaling, $S \cdot M^{-1}$, is nearly a satisfactory body mass-adjusted index of BP (14). This finding for BP is also puzzling and would require further detailed study for explanations.

While apparent agreement is reached regarding the use of the 2OP model for either Olympic or powerlifting events for women, perhaps the AM should not be so readily discarded even for elite weightlifters. Since women's weightlifting in general is a relatively new sport compared with the men's, then the natural evolution of world records improving in relatively large increments may be presently occurring. That, coupled with the statistical probability that far fewer competitors are found in the lightest and heaviest weight categories, can lead one to argue that those in the middle weight classes have the most competition and therefore are probably closer to the physiologic limit for human performance. If this were true, then the "depressed" values for the lightest and heaviest lifters would contribute to a pattern similar to that found in the present data or in those of Batterham and George (4). This would also explain the better fit for the 2OP which favors depressed values for the extremes. Indeed, contest results of the 1997 IPF Women's World Championships (open to all women over the age of 14 yr), obtained from the aforementioned IPF Internet site, indicates that while 23 women competed in the lightest (44- and 48-kg) and heaviest two (90- and 90+-kg) weight classes, 38 women competed in the middle four (56-, 60-, 75-, and 82.5-kg) weight classes. A similar trend was found for the men's 1997 World Championships with 42 men competing in the lightest plus heaviest two (52-, 56-, 125-, and 125-kg) and 84 in the middle four (67.5-, 75-, 82.5-, and 90-kg) weight classes.

More importantly, to our knowledge, no satisfactory explanation exists for the superiority of the 2OP approach other than it displays a better statistical fit. Furthermore, acceptance of the 2OP for modeling of such world records, is not without noteworthy artifact. For example, Figure 1 indicates that, for the 2OP applied to the DL and SQ, the world record lifts would be expected to plateau and then decrease as body mass increases beyond 90 kg, a problematic finding from a theoretical perspective. The AM, on the other hand, cannot plateau, although its slope can certainly decrease as body mass gets large. For this and some of the aforementioned reasons, AM has significant theoretical support (3,8,9,17,20) and, perhaps less importantly, provides for a more convenient index of performance (i.e., $S \cdot M^{-b}$) that facilitates group or individual performance. Therefore, one can make the argument that the AM is still preferred over the 2OP when comparing body mass-adjusted performance among world record holding women powerlifters because the 2OP's statistical superiority may be a function of statistical fit and subject numbers in weight classes. In fact, use of the 2/3 body mass exponent can be considered more appropriate than the empirically derived exponents because the latter are sample specific and the former is firmly grounded in a theoretical base.

Nevertheless, as shown in Table 3, determination of the world's strongest women in each lift, body mass-adjusted, is possible with either model. The top two performers in each lift vary depending on the model chosen for all except the DL in which the same competitors are chosen for first and second place. As the total lift is perhaps most indicative of overall strength one can argue that Carrie Boudreau (U.S., 56-kg weight class) is the strongest woman in the world because she attained first place in the TOT with either model.

Interestingly, higher order polynomials can be used to provide even better model fits for such data (4). Such statistically appealing modeling should, in our view, be approached with extreme caution. The nature of third, fourth, and higher polynomial curves is such that as body mass increases, slopes can increase, decrease, then increase again. This presents two problems. First, this can happen to accommodate an exceptional lift among the middle weight classes but actually penalizes this lifter by making her lift as close to the best fit curve as others (body mass-adjusted achievement is based on the vertical distance above the best fit curve). In other words, such higher order modeling decreases this exceptional lifter's body mass-adjusted score. Second, no satisfactory physiological explanation exists to support these models. As previously explained, we believe that the relatively higher number of competitors in the middle weight classes is a plausible mechanism for their higher body mass-adjusted scores when using AM.

We conclude, then, that model selection is critical to determining the world's strongest women, body mass-adjusted, in powerlifting events. If statistical fit is most important, then the 2OP is the obvious choice. If theoretical soundness is desired, then perhaps the AM is warranted. Within the AM realm one can determine sample-specific exponents as was done in this investigation or one can use the theoretically based 2/3 exponent. The former takes into account more the independent influence of body mass whereas the latter is not subject to outlier performance within the sample. While the apparent penalty for the AM is on those lifters at the extremes, this is perhaps acceptable as fewer competitors worldwide are likely available in these weight classes. Regardless of empirically-based model, however, the strongest body mass-adjusted woman in the world is arguably Carrie Boudreau of the United States in the 56-kg weight class.

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